Space Quantum Gravity Gradiometer: A Progress Report

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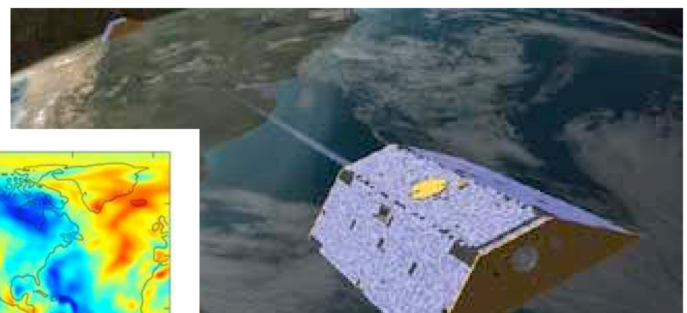
Gravity Field Mapping in Space

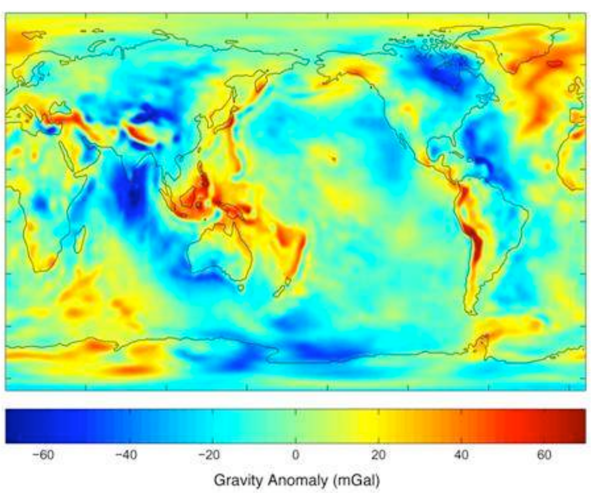
Earth Observatory for Climate Effects

- Surface and ground water storage
- Oceanic circulation
- Tectonic and glacial movements
- Tidal variations
- Earthquake monitoring

Solid Earth and planetary interior modeling

- Lithospheric thickness, composition
- Lateral mantle density heterogeneity
- Deep interior studies
- Oscillation between core and mantle





Gravity anomalies from 111 days of GRACE data

3-D simulation of compressible mantle convection

Basic Gravity field Quantities and Observables

The primary concern here is the static gravity field produced by a mass distribution. By mapping the field, it's possible to extract mass distribution information.

Gravity gradient G,

$$G_{ij} = \partial_j g_i = -\partial_{ij}^2 \phi(r)$$

gg is a 3x3 tensor, with 5 independent parameters

Measurable directly by gradiometer or satellite-satellite tracking.

Unit: Eötvös (EU) = 10^{-9} /s^2.
Near Earth surface, about 3000 EU.
A person 1 meter away produces about 1 EU.

Overall objective:
Obtain information about $m_i(r_i)$ from $\Phi(r)$

Gravity potential

$$\phi(\vec{r}) = \sum_i G \frac{m_i}{\left|\vec{r} - \vec{r}_i\right|}$$

The potential difference can be measured by leveling.
The equal potential surface, approximate the mean sea level, is the **geoid**. This is measured by tide gauges, satellite altimetry, ...

Gravity acceleration g:

$$g = -\nabla \phi(r)$$

Measurable directly by gravimeter
Unit: m/s^2, 1mgal = 10^{-5} m/s^2,

Why Gradient Measurement, Existing Devices

Direct acceleration measurement requires absolute vibration isolation - due to Einstein's Equivalence Principle: the frame acceleration can not be distinguished locally from gravitational acceleration.

A gradiometer measures the difference in gravity, with the common local acceleration subtracted.

$$\left[\left(g(x_1)+a\right)-\left(g(x_2)+a\right)\right]/\,d=\Delta g_{12}\,/\,d$$

Traditional mechanic devices:

• Torsion balance, measuring large local gradient anomaly for prospecting.

• Falling corner cubes: limited precision.

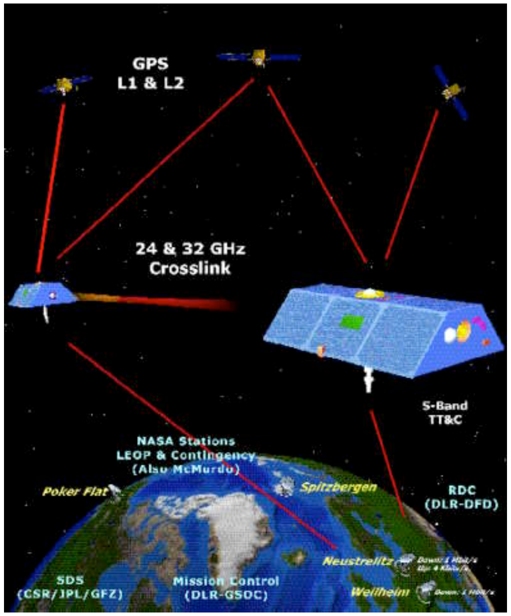
• Mass-spring accelerometer pairs: Lockheed-Martin UGM, air-borne survey of geophysics.

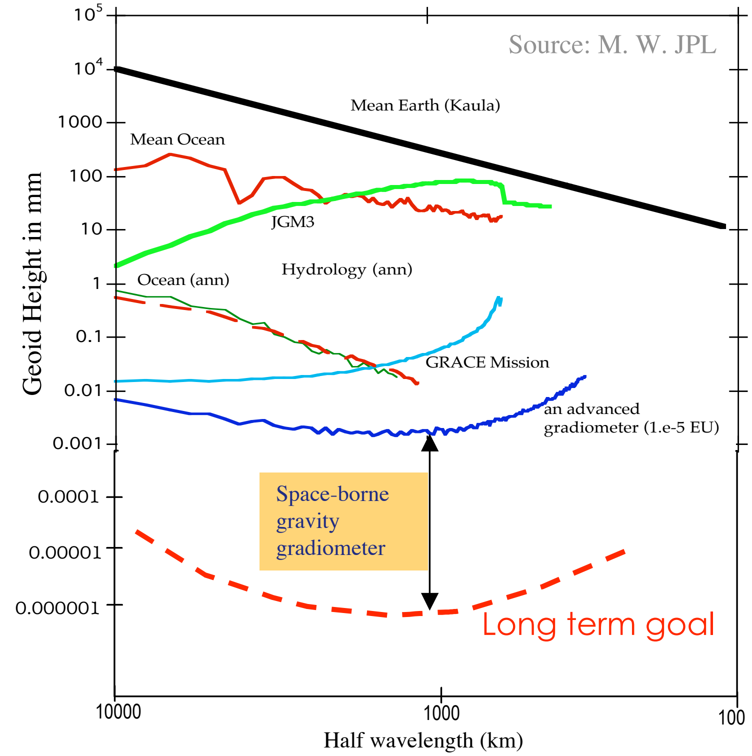
• Superconducting transducer: 0.1 EU/√Hz, cryogen, poor long-term stability.

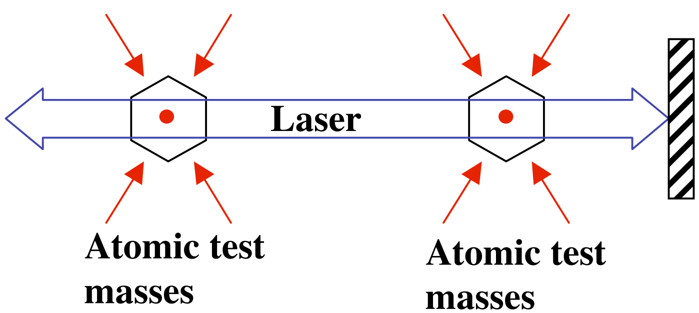
Eotvos's torsion balance

Bell Geospace

Gravity Survey with Cold Atom Gradiometer







Gravity gradient measurement configuration with atom interferometers

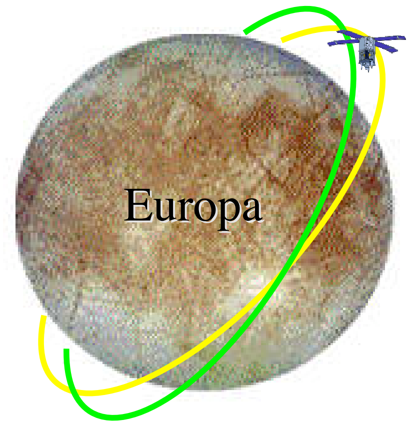
Single satellite:
(L=10m) < 10^{-3} EU/Hz$^{1/2}$

Long baseline:
(100 m) < 10^{-4} EU/Hz$^{1/2}$

Satellite formation:
(100km): < x10^{-7} EU/Hz$^{1/2}$

Planetary Exploration

Gravity survey and resource exploration

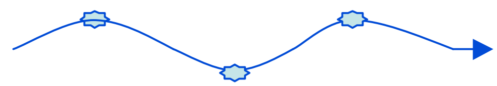


"Hidden Ocean beneath?"
With a gradiometer at 500 km altitude after several months averaging, the presence of a 5000 tons of water/ice beneath the surface can be determined and located in 2D, and the depth of a $30 \times 30 \times 1$ km^3 sub-surface lake can be determined to 30 m accuracy.

Mars gravity field mapping,
Supporting Mars exploration.

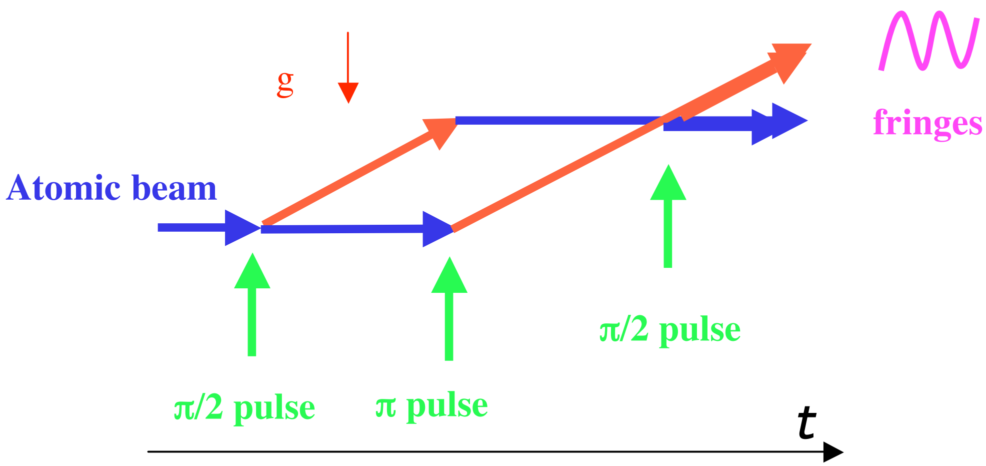
Atom Interferometer as an Accelerometer

Quantum particle-wave duality



de Broglie wave: $\lambda_{dB}=h/mv$

Atom-wave Mach-Zehnder Interferometer



Splitter/mirror functions are accomplished by interaction with laser pulses.

(M. Kasevich and S. Chu *Phys. Rev. Lett.* vol. 67, p.181, 1991)

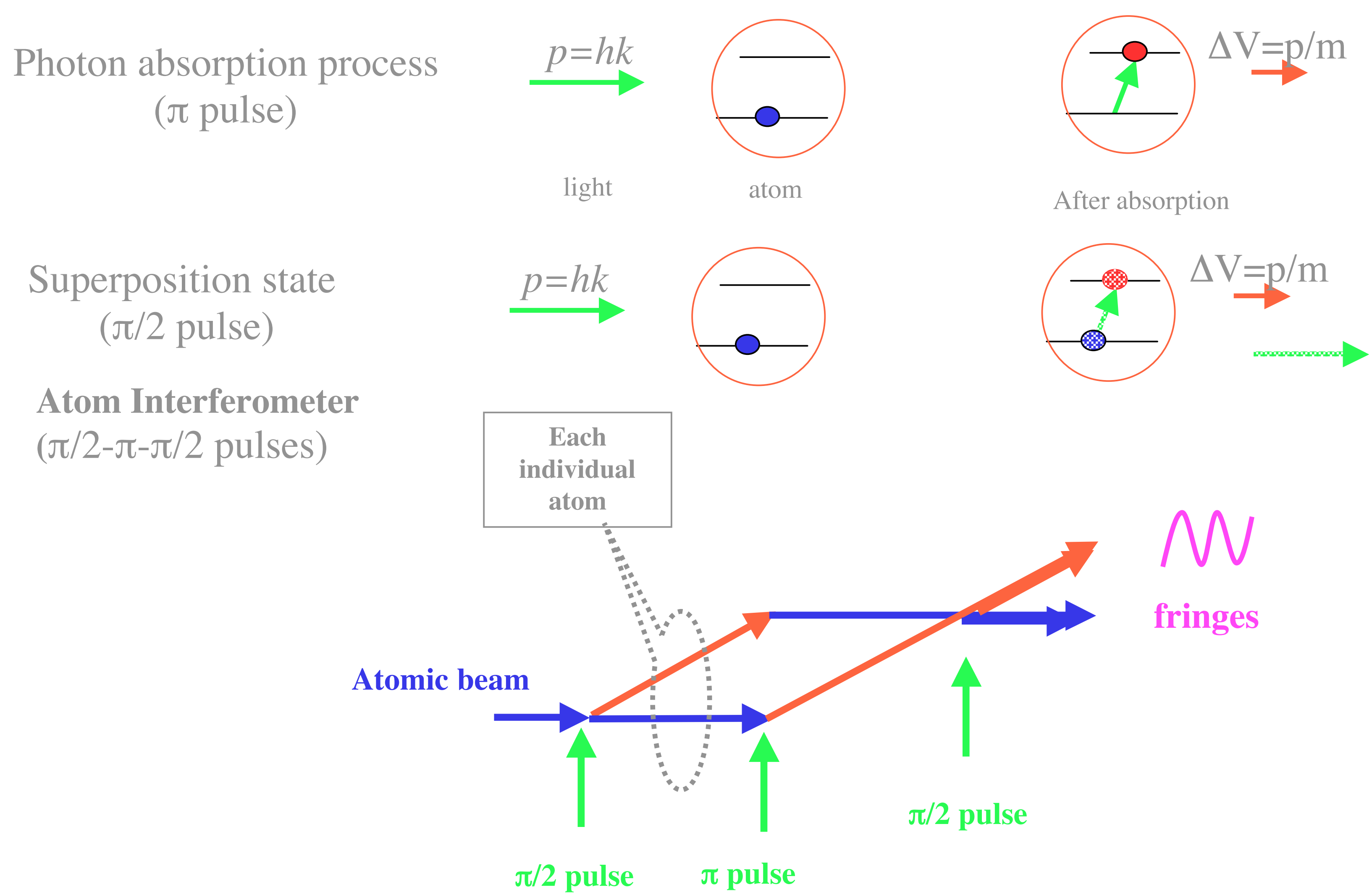
No acceleration, total phase shift difference is $\Delta\Phi = 0$;

With an acceleration g, the phase difference is

$$\Delta\Phi = 2kgT^2$$

where k is the laser wavenumber and T the time interval between laser pulses.

Understanding Atom-Wave Interferometer Using Light Pulses



Unique Space Environment

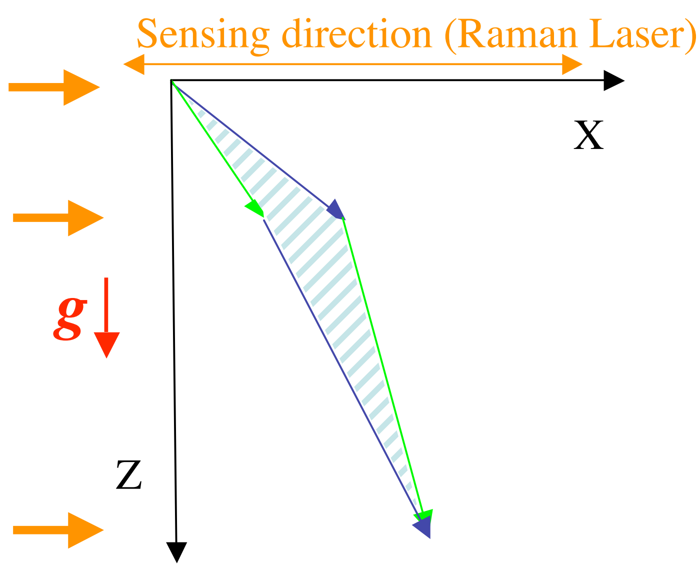
Remote space operations and environment present technical challenges. On the other hand, the unique environment also provides opportunities.

- **Space offers freefall microgravity environment**
- **Large gravity variation possible**
- **Minimal mechanical disturbance environment**
- **Space applications often demand high sensitivity and stability**

Performance Enhancements in Space (multi component sensing)

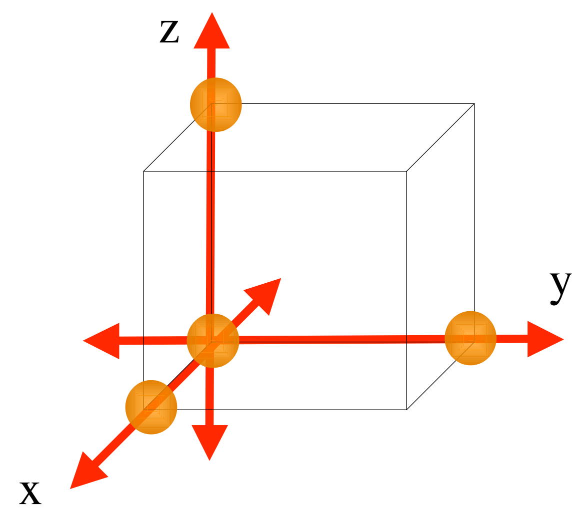
Absence of large g acceleration bias makes the orthogonal measurements symmetric.

On the Ground



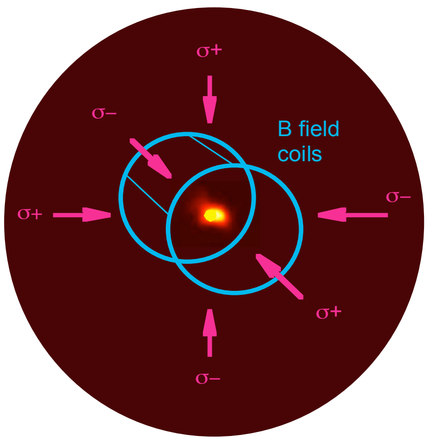
Large vertical spatial extent,
Finite area results - Sagnac loop

In Space

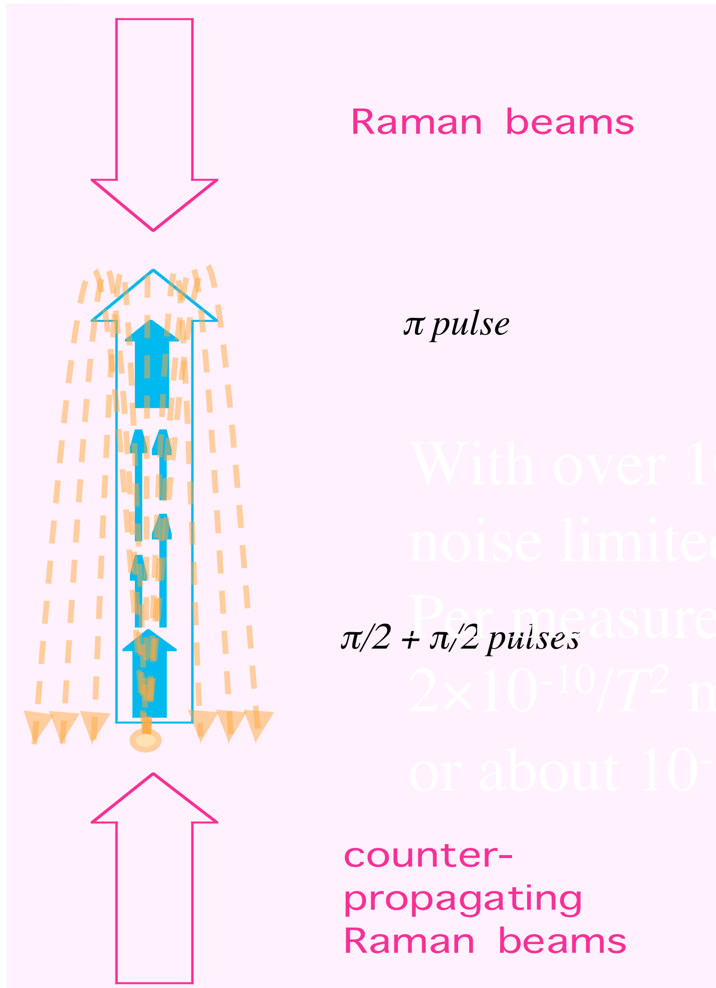


All three direction measurements are similar.

Cold Atom Experiments on the Ground
(Atomic Fountain)



Trapping and cooling



Vertical acceleration measurement.
The fountain provides twice the interaction time

$$\delta g = \frac{1}{2kT^2}\frac{\pi}{SNR}$$

With over 10^6 detectable Cs atoms, the shot-noise limited SNR ~ 1000.
Per shot sensitivity ≈ $10^{-10}/T^2$ m/s^2, or about $10^{-11}/T^2$ g.

Performance Enhancement in Space (Long Interaction Time)

In microgravity, atoms do not fall away fast, allowing much longer interrogation time. Because of **$\delta g \propto 1/T^2$**, *the sensitivity gains significantly with the increasing interrogation time* ***T***.

For example: in microgravity, 10^{-13} g $\mathrm{Hz}^{-1/2}$ possible with >10 s interrogation time.

Even in the limit of atom number loss due to finite temperature:

$$SNR = \frac{1}{\sqrt{N_{atom}}} \propto \frac{1}{\sqrt{T^3}} \qquad \delta g = \frac{1}{2kT^2}\frac{\pi}{SNR} \propto \frac{1}{\sqrt{T}}$$

The sensitivity is gained by a longer interrogation time.

AI Accelerometer Phase Shift

<u>For atom interferometer accelerometer</u>

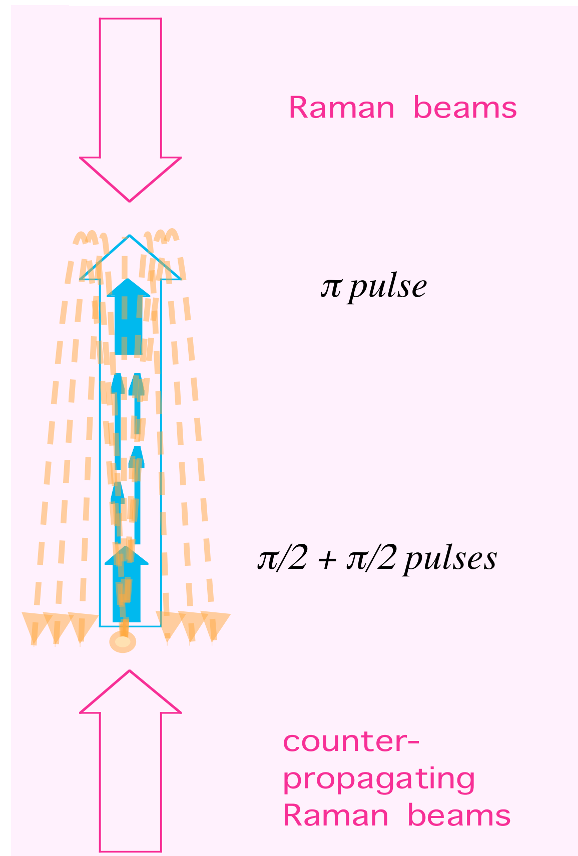
$$\Delta\Phi = 2\,k\,a\,T^{2}$$

- Independent of atom initial velocity
- *k*, the laser wavenumber is the only reference parameter
- Sensitivity goes with T^2

With over 10^6 atoms, the shot-noise limited SNR ~ 1000.
Per shot sensitivity = $2\times10^{-10}/T^2$ m/s^2, or about $10^{-11}/T^2$ *g*.

Great enhancement of the sensitivity can be gained in microgravity in space!

<u>Atomic fountain on ground</u>

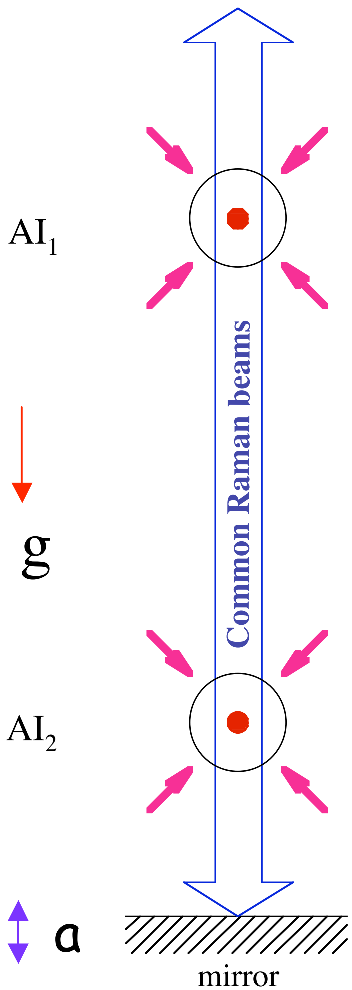


For example: in microgravity, 10^{-13} g Hz$^{-1/2}$ possible with >10 s interrogation time.

Gravity Gradiometer

A gradiometer measures the difference in gravity, with the common local acceleration subtracted.

$$\left[\left(g(x_1)+a\right)-\left(g(x_2)+a\right)\right]/\,d = \Delta g_{12}\,/\,d$$



$\Phi_1 = 2k(g_1+a)T^{\,2}$

$\Phi_2 = 2k(g_2+a)T^{\,2}$

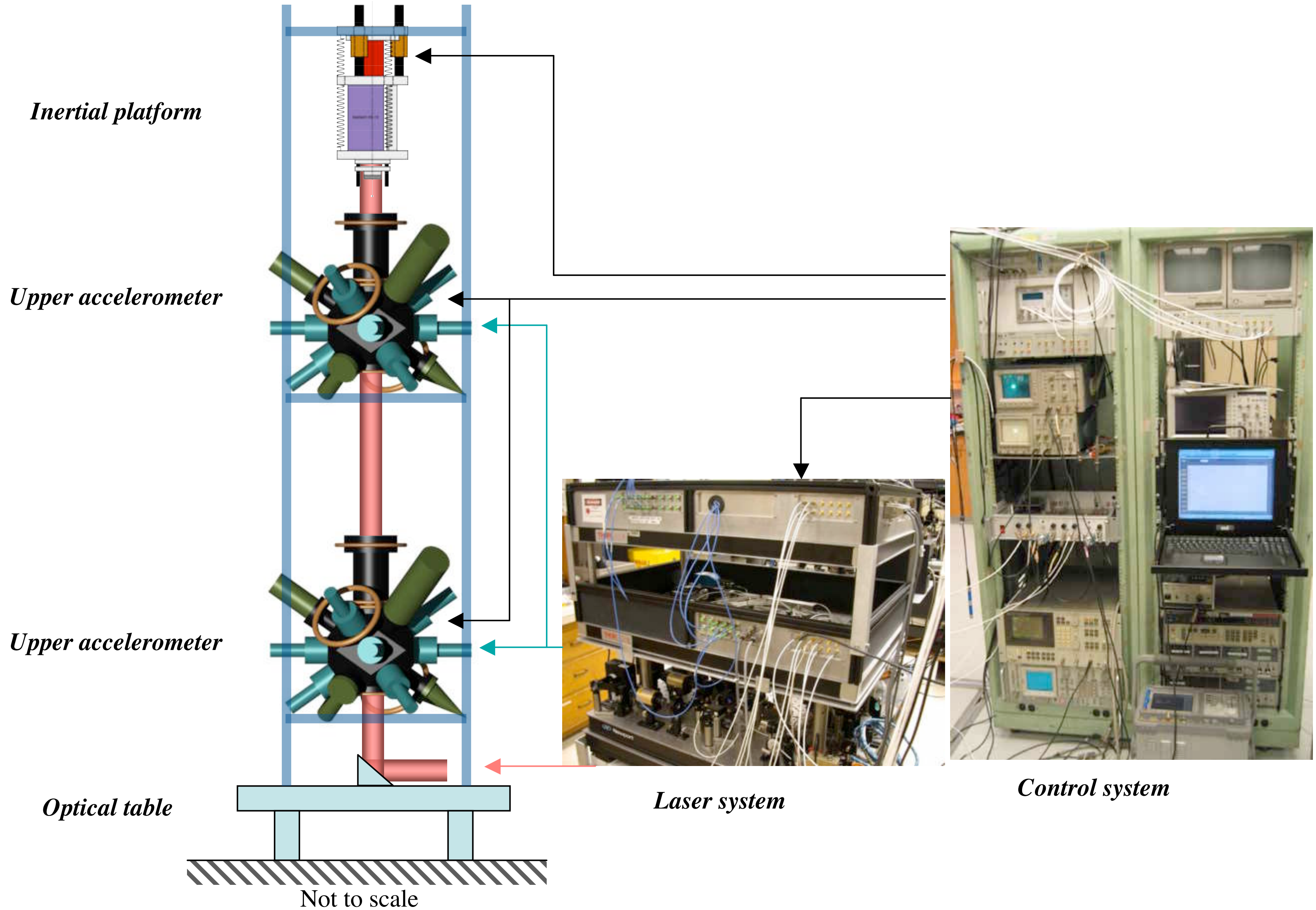
$$\boxed{\Delta\Phi_{12} = 2k\,(g_1 - g_2)\,T^{\,2}}$$

The common reference acceleration is cancelled out[(1)], which allows the gradiometer to be used on moving platforms such as spacecraft.

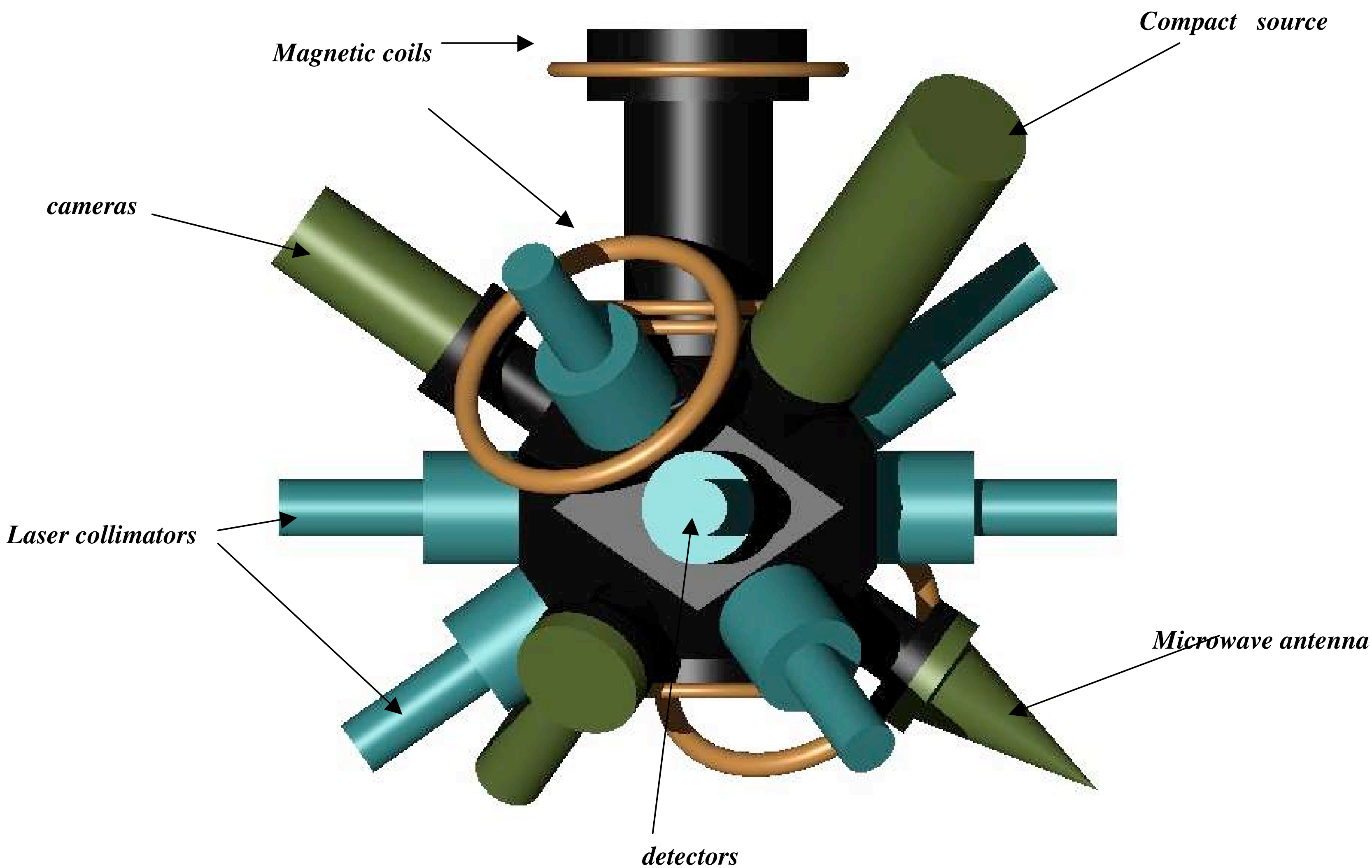
The common-mode suppression has been demonstrated to be greater that 140 dB ! [(2)]

(1) M. J. Snadden et al. PRL **81**, 971 (1998).
(2) M. Kasevich, Private communication.

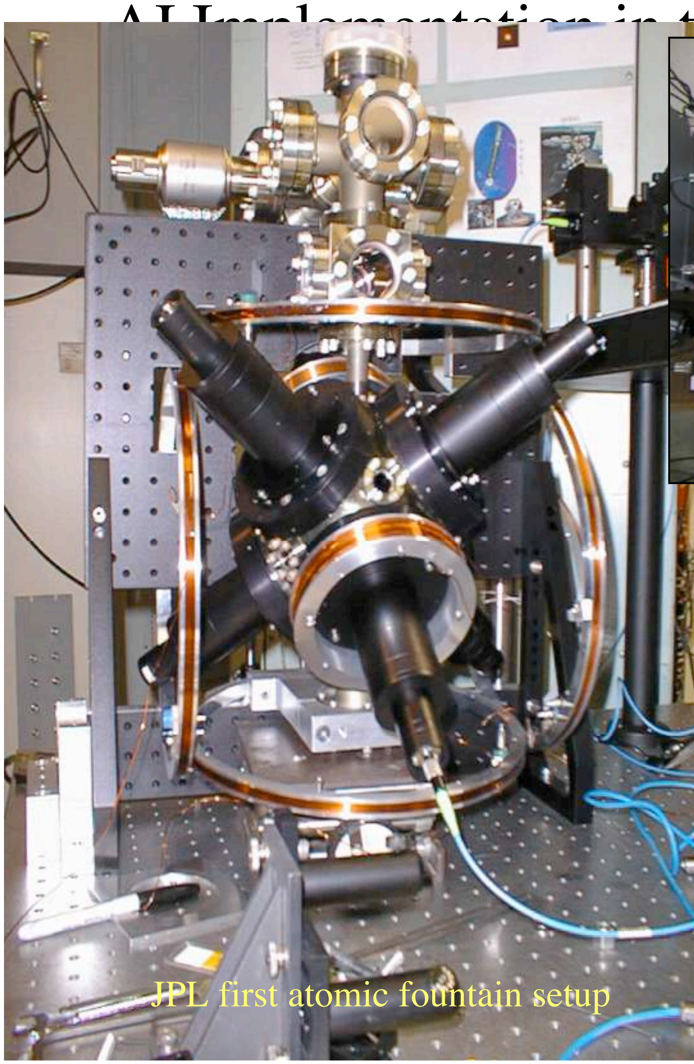
System Design



Assembled Look of Atomic Fountain

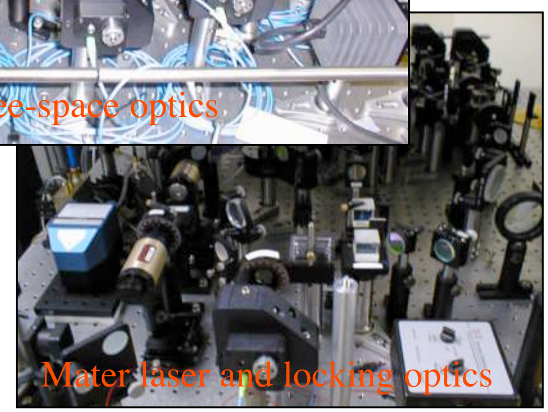


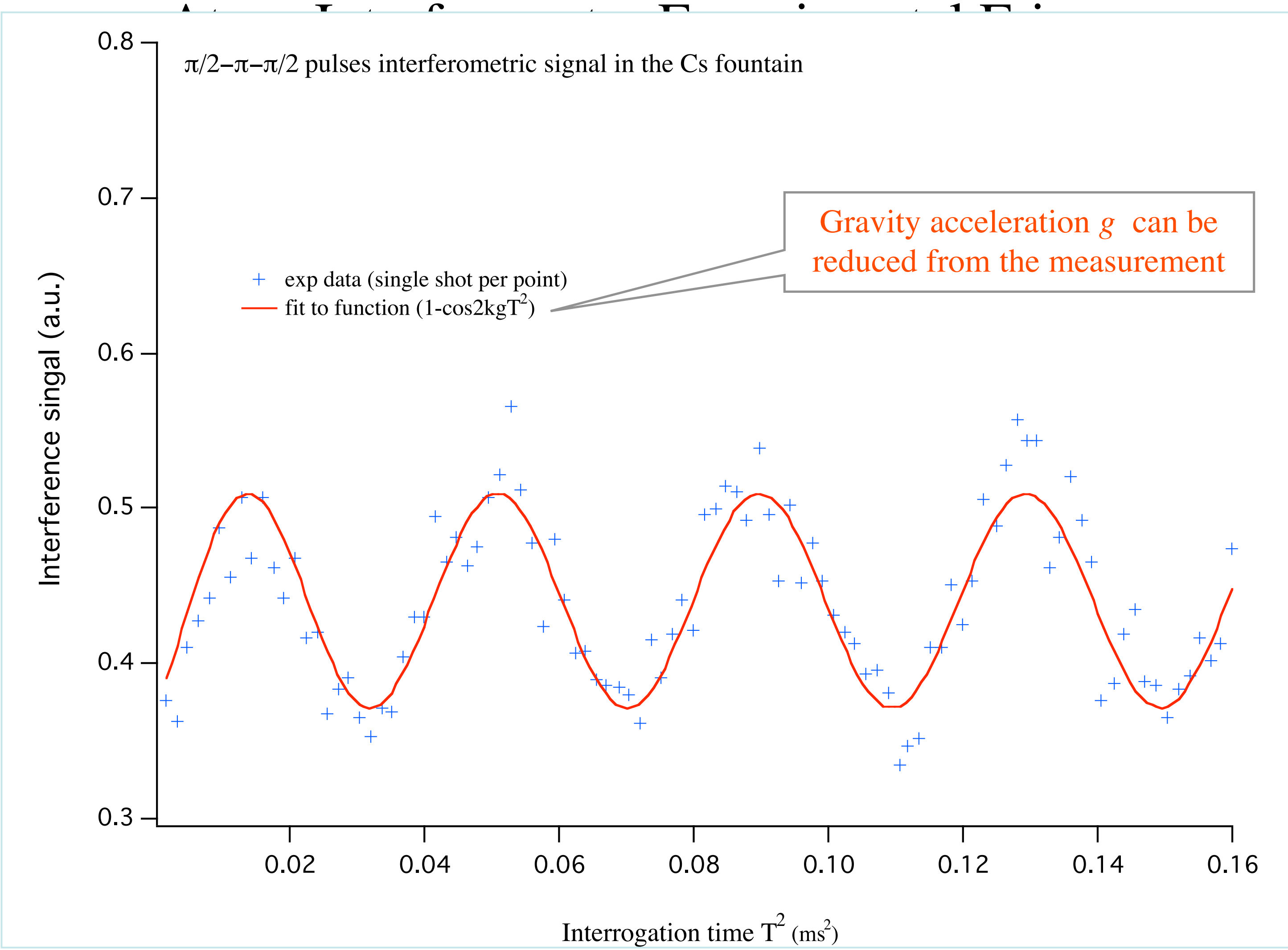
AI Implementation in the First JPL Atomic Fountain


JPL first atomic fountain setup

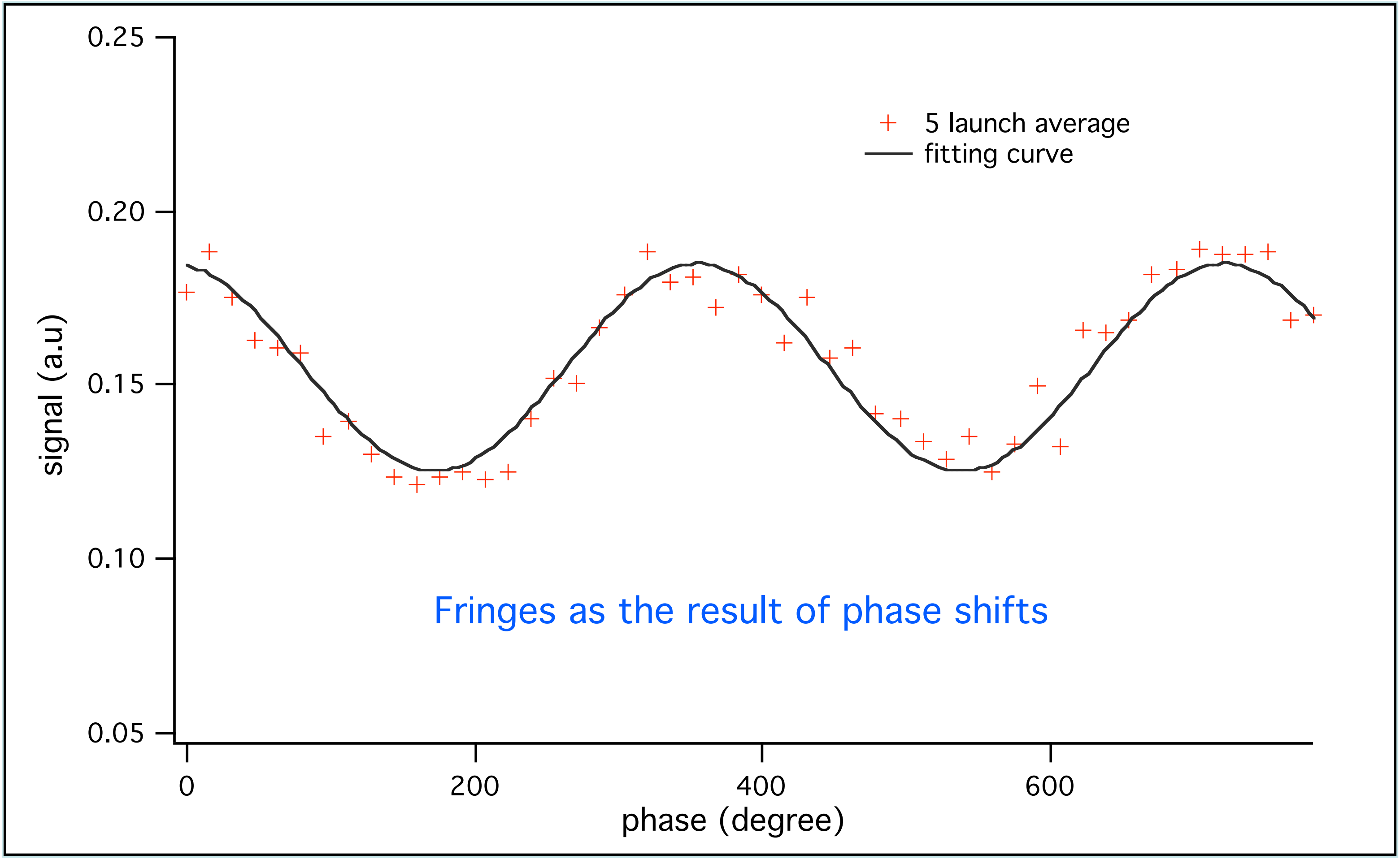

Injection-locked Raman lasers


Free-space optics


Mater laser and locking optics

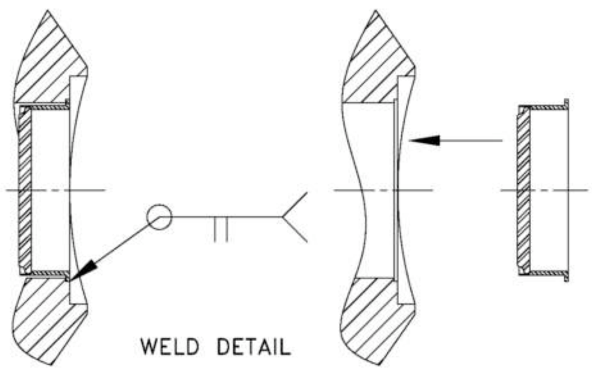

π/2–π–π/2 pulses interferometric signal in the Cs fountain
Gravity acceleration g can be reduced from the measurement
exp data (single shot per point)
fit to function (1-cos2kgT²)
Interference singal (a.u.)
0.8
0.7
0.6
0.5
0.4
0.3
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
Interrogation time T² (ms²)

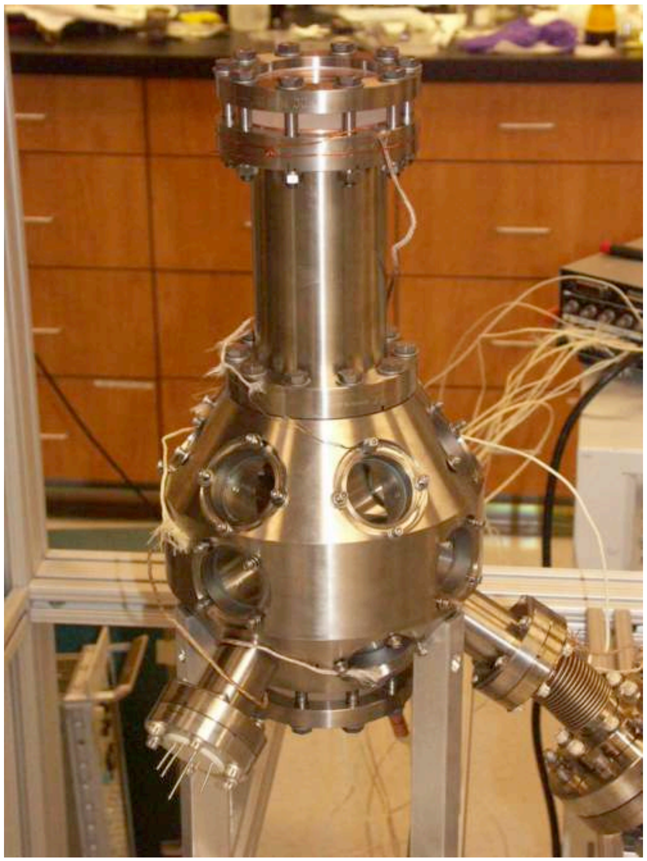
Interference Fringe Change as the Simulated Phase Changes



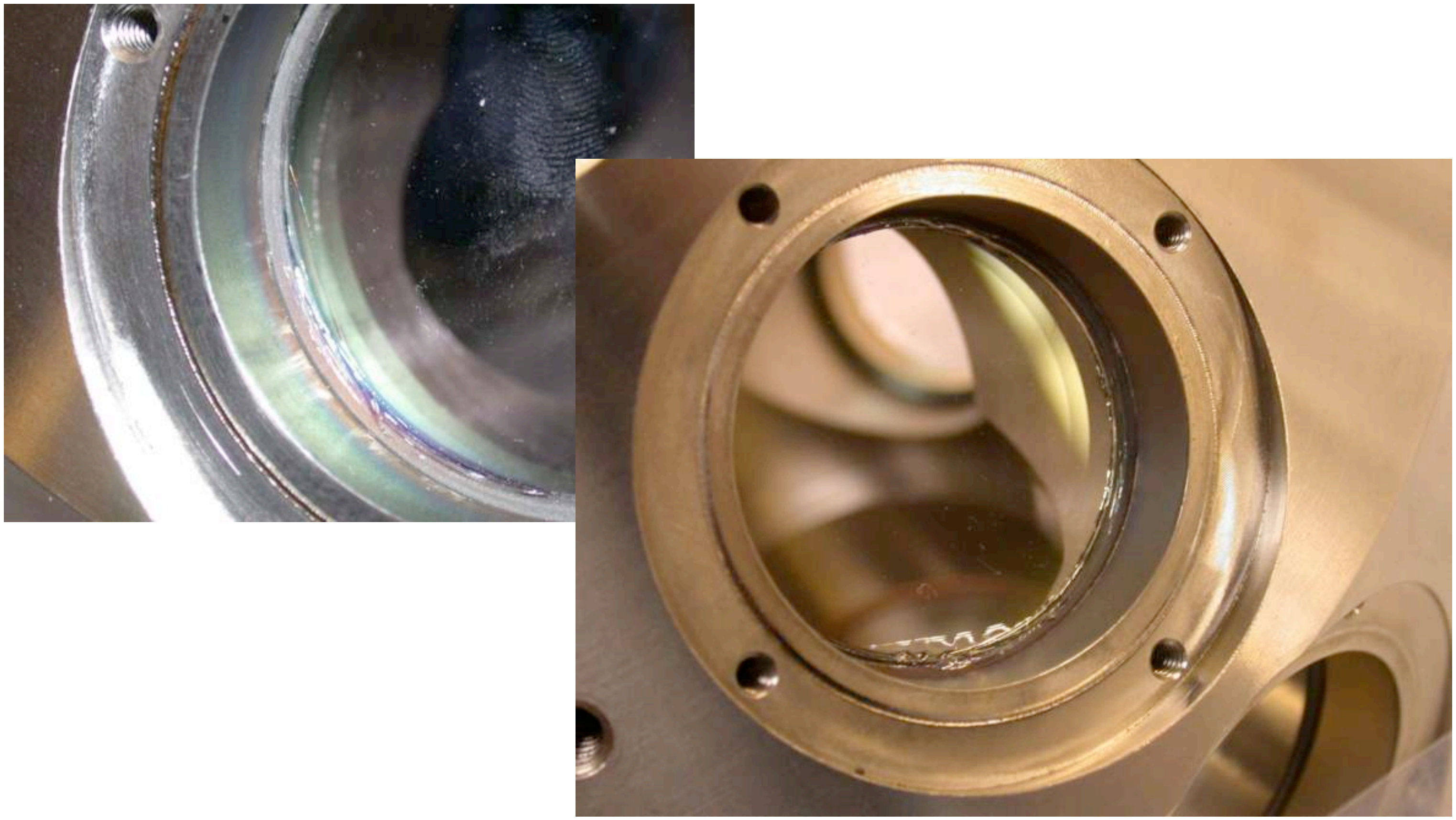
New Ti Vacuum Chamber

Design requirements:
UHV compatible
Non-magnetic
13 high quality viewports
Custom window MK seals





Chamber Delivered with Defects



Ti Chamber and the Physics Package in Preparation

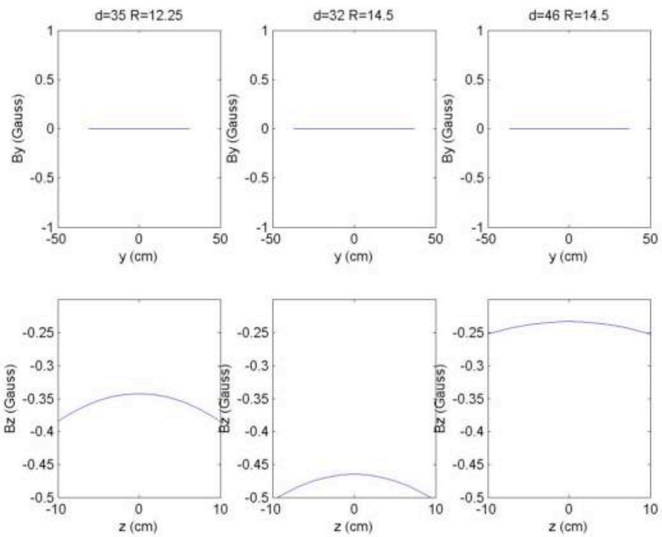
Ti chamber on the setup support frame

Cold source attachment

Gradiometer Framework

Magnetic Field Coils

Modelling of MOT coils

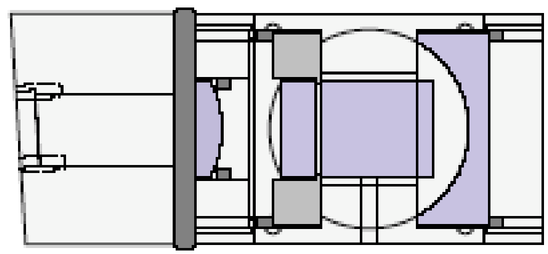


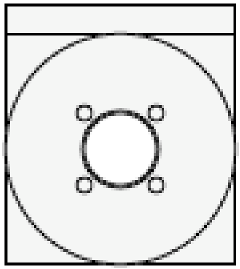
Compensation coils made

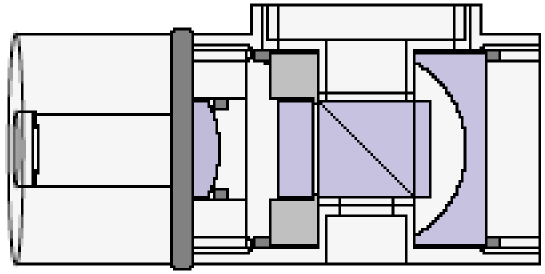
Better Collimator Design

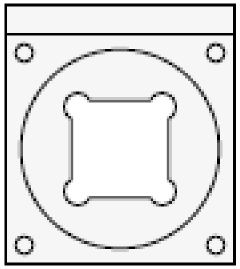
New collimator design with stable and flexible monitoring port design

(based on lessons learned from the current collimator design)

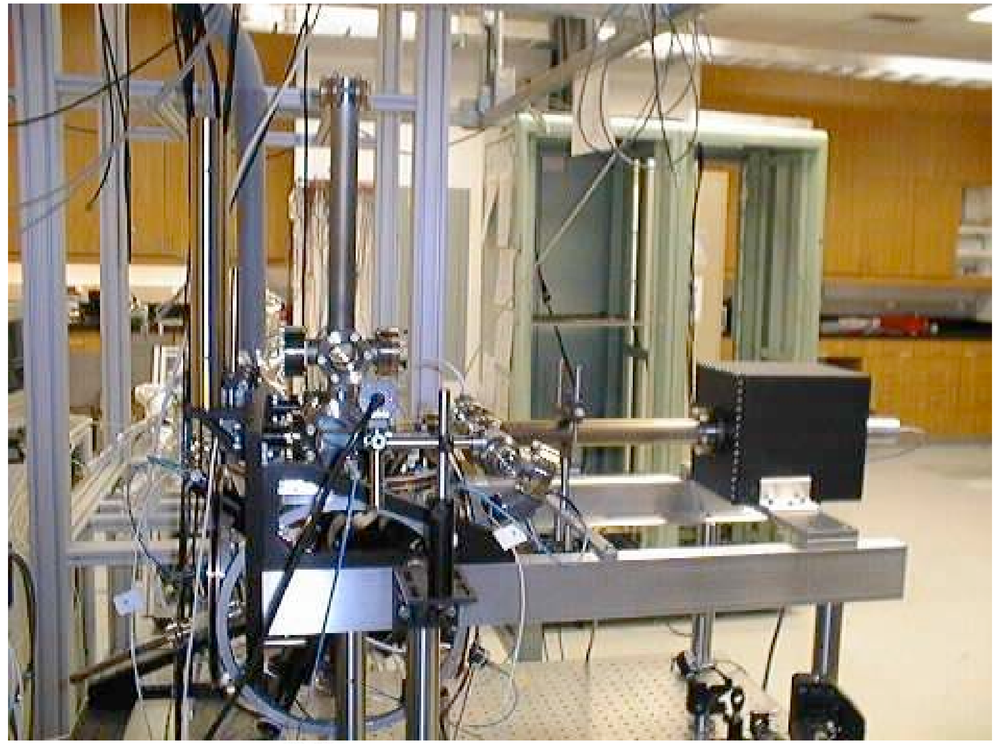


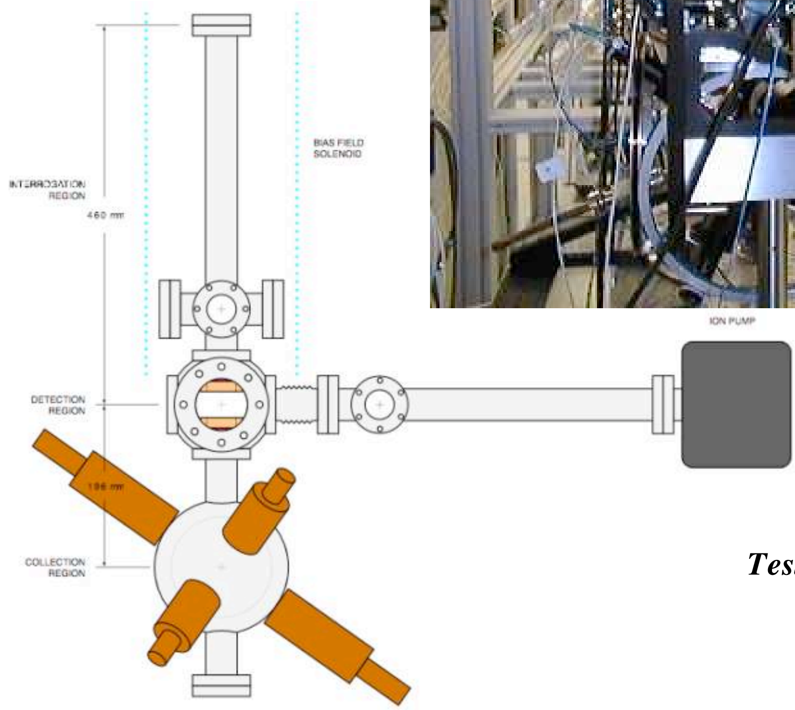






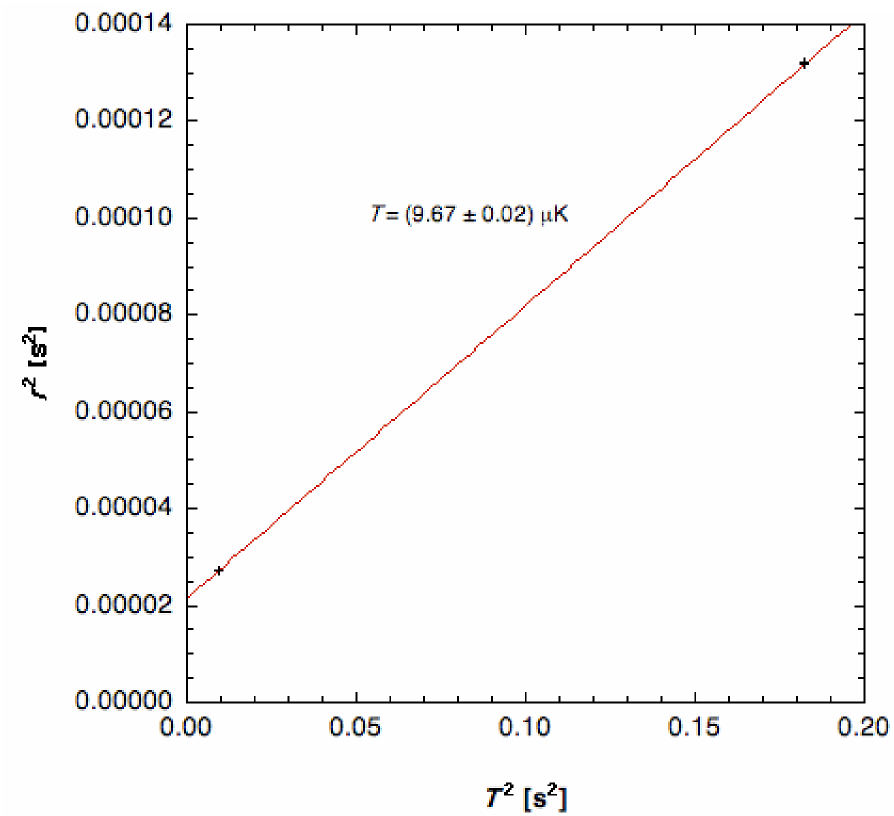
Test chamber design and implementation

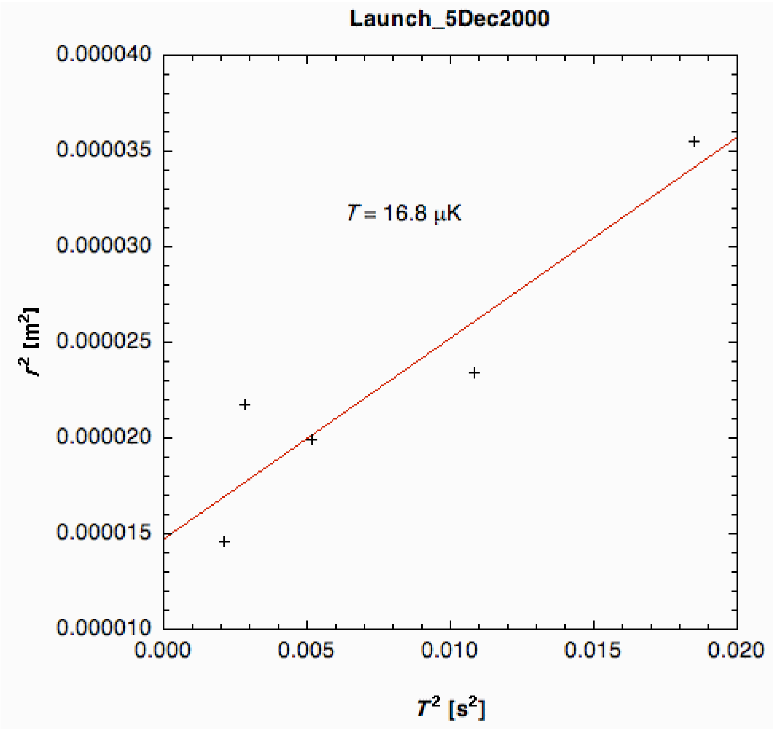




Test chamber design and implementation

New Launch Temperature Measured

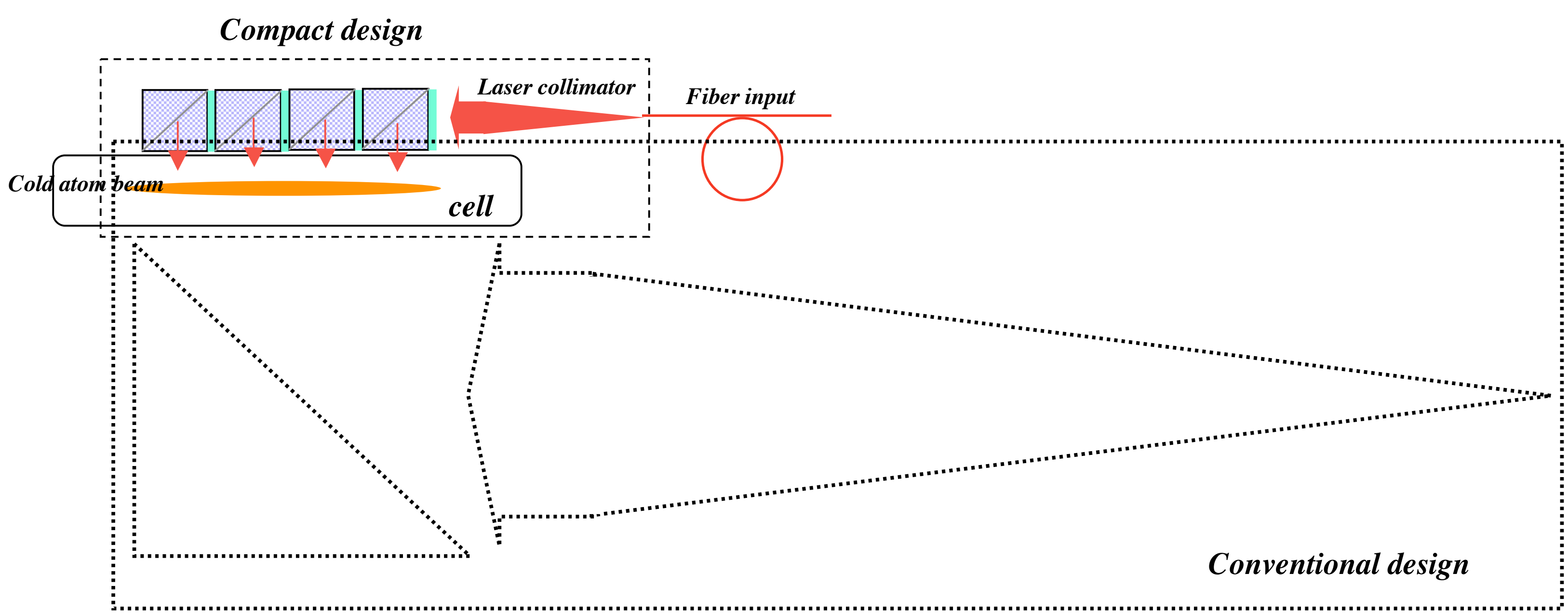




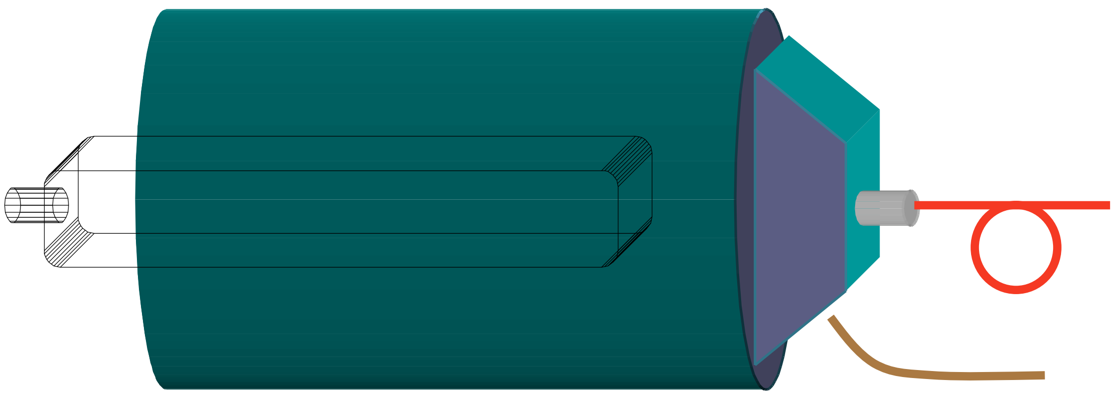
Compact Source Design Concept

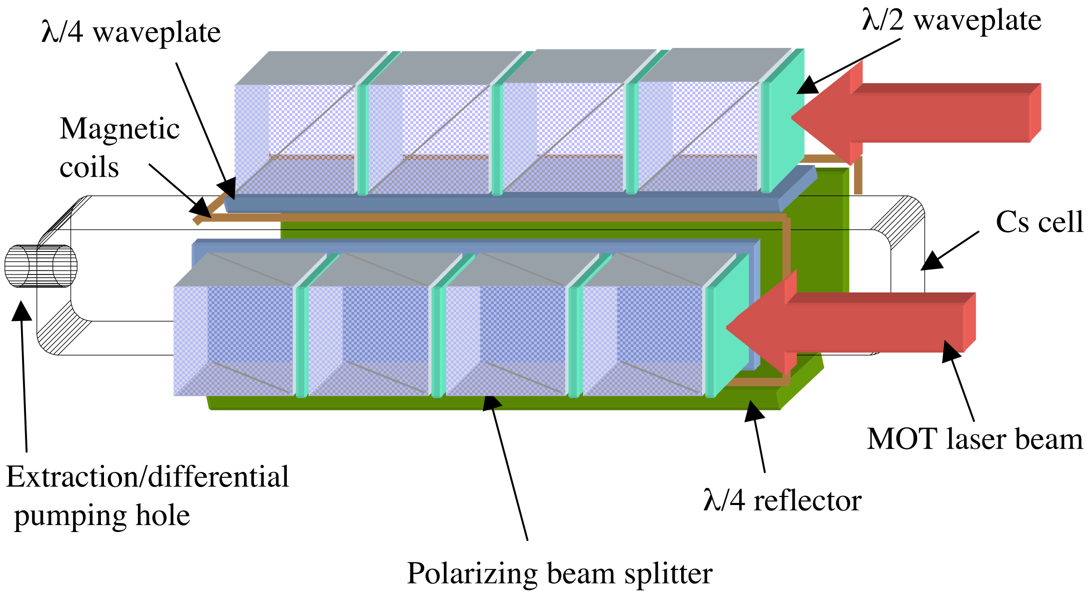
<u>Motivation:</u>

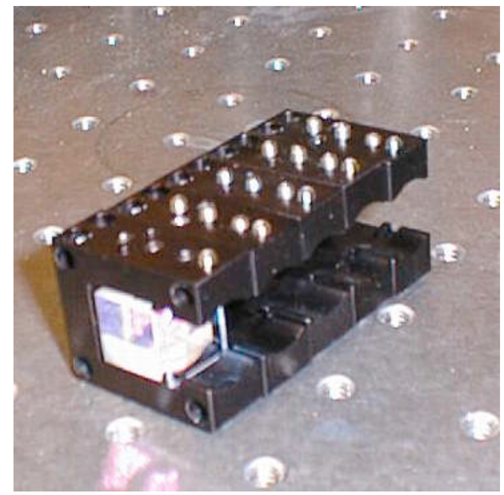
1. Allows differential pumping, and hence, UHV interaction and detection regions.
2. Offers high flux and faster loading.
3. To be used as a simple and compact attachment.



Compact Source Design Concept



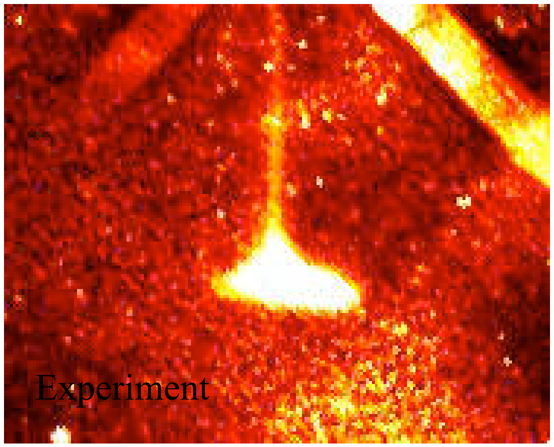


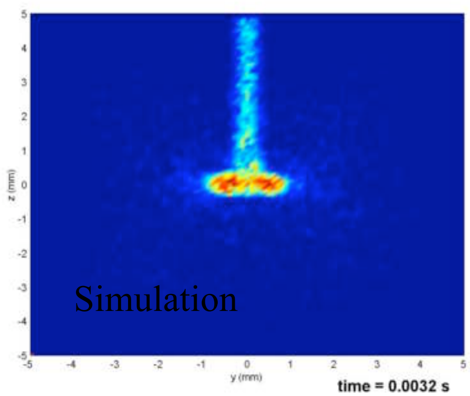


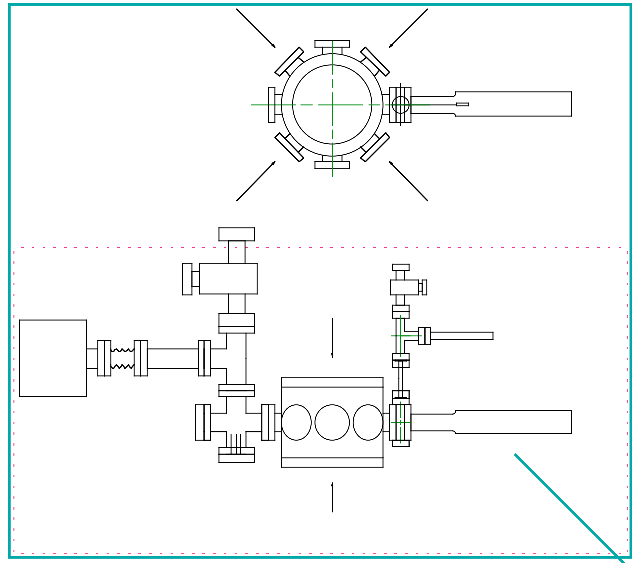
a train of 2D MOT in series.

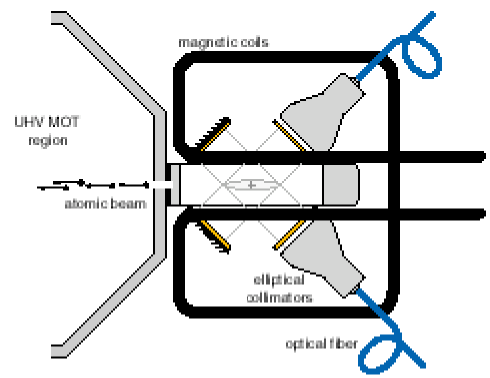
Compact Source/Current Effort

Experiment vs Simulation

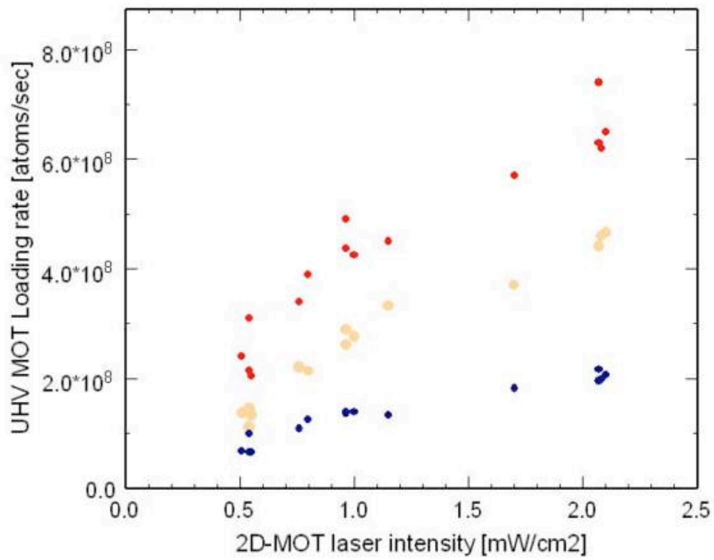


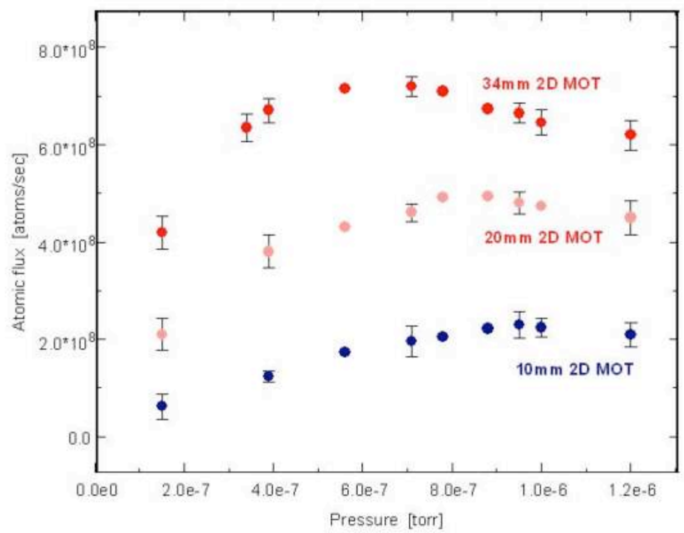


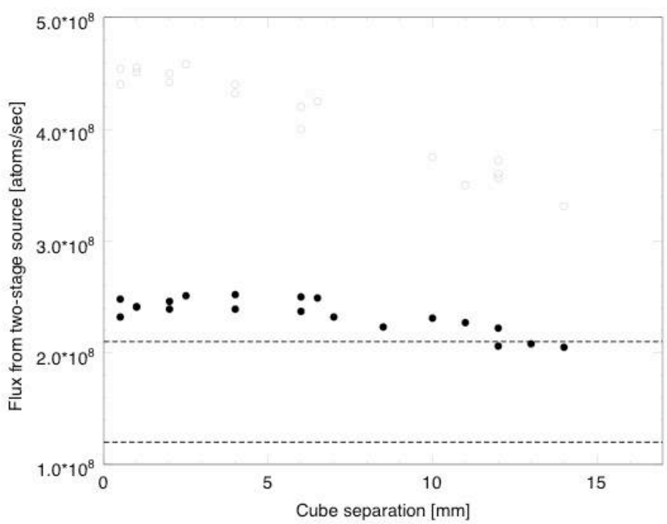


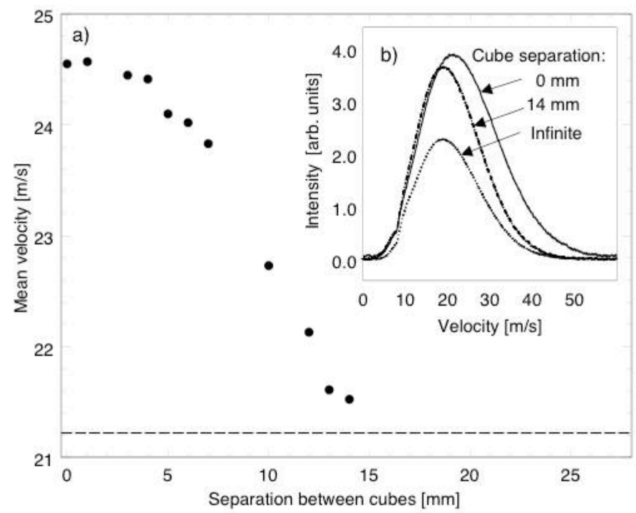


Laser System Module Tests









A Paper on the Compact Source to be Published

A compact multi-stage 2D-MOT atom source

J. Ramirez-Serrano, N. Yu, J.M. Kohel, J.R. Kellogg, and L. Maleki
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA 91109 USA
(Dated: April 30, 2004)

A compact atomic beam source based on a multi-stage 2-dimensional magneto-optical trap (2D-MOT) scheme has been developed and characterized. The multi-stage 2D-MOT design greatly reduces the overall size of the source with optics while maintains a high flux of atoms. A continuous Cs atomic beam with a flux up to 1.45×10^9 atoms/sec has been demonstrated with a low mean velocity of 15 m/s . The entire source setup including optics can fit into a $4 \times 4 \times 5$ cm^3 volume. This source will be useful for cold atom-based devices.

PACS numbers: 32.80Pj, 33.80 Ps, 34.50 Rk

A separate high-flux atom source for loading a magneto-optical trap (MOT) in ultra-high vacuum (UHV) has been the choice of implementation in many cold atom experiments. Such an approach is advantageous because it allows one to achieve a high loading rate of the UHV MOT while keeping the background pressure low. While there have been several distinct approaches of cold sources[?], A 2D MOT source from a higher pressure vapor cell is the simplest and most effective for alkaline atoms.[1–7] In a conventional 2D MOT configuration, the length of the 2D MOT determines the overall optics size of the laser beams needed as illustrated in Fig. 1.[10] Therefore, the cold beam source can be a bulky addition to an experimental setup. In addition, in-vacuum optics are often used.[?] This kind of arrangement is unacceptable in many practical devices and applications.

In this paper, we report the demonstration of a new configuration of compact cold beam source. The device consists of multiple stages of 2D MOTs. Each individual MOT is short in length, requiring a correspondingly small laser beam size. A chain of such small MOTs is used to achieve a total high flux. By strategically distributing the laser beam to all MOTs, the overall size of the atom source is significantly reduced compared to

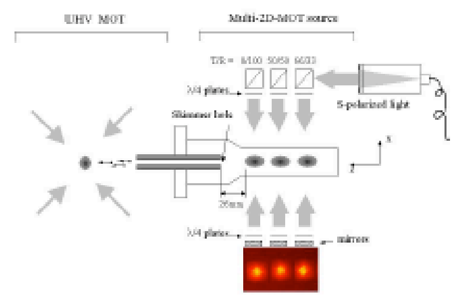


FIG. 1: Schematic of the experimental apparatus, including the multiple 2D-MOT source of cold atoms and UHV MOT. See text for the description of the components

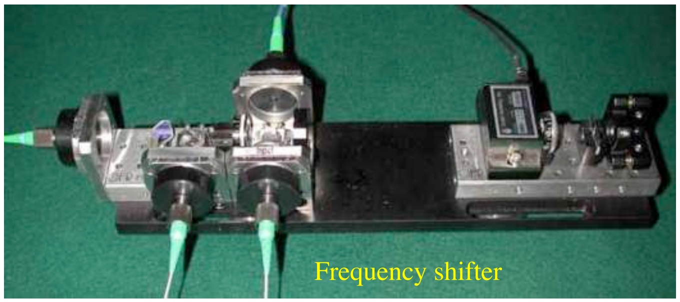
extraction arrangement proves effective when the source is operating at a high vapor pressure.

Each individual 2D MOT is formed by a pair of retro-reflected laser beams formed by a beam splitting cube and the retro-reflecting mirror. Quarter wave plates are inserted in front of each beam splitter and mirror to pro-

Modular Laser and Optical System

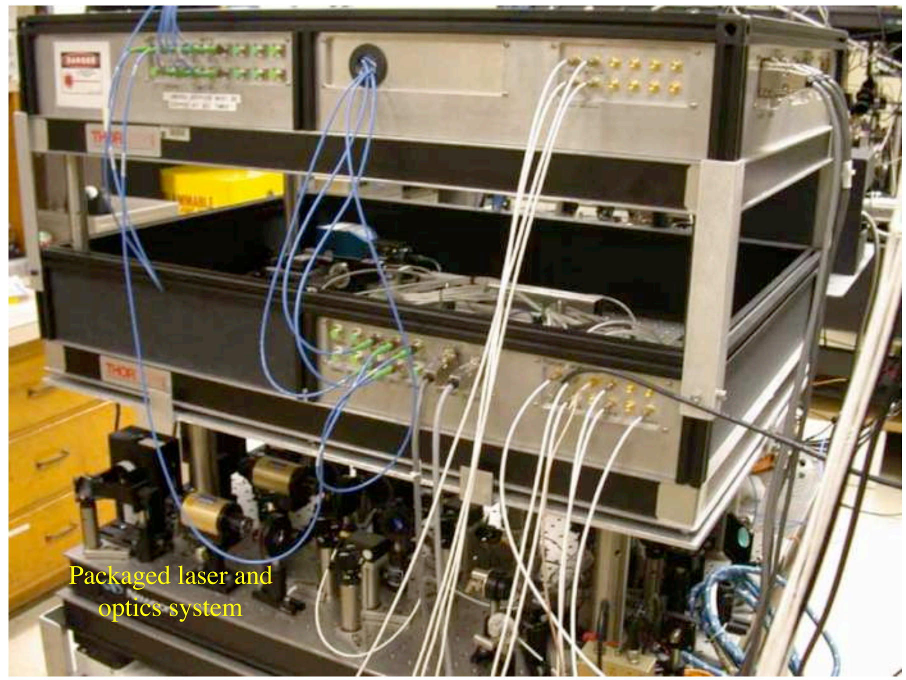
Design objective:

1. Compact and portable system;
2. Robust and stable over long term and out-of-lab environment;
3. Readily replaceable and re-configurable;
4. All commercially available parts.


Frequency shifter

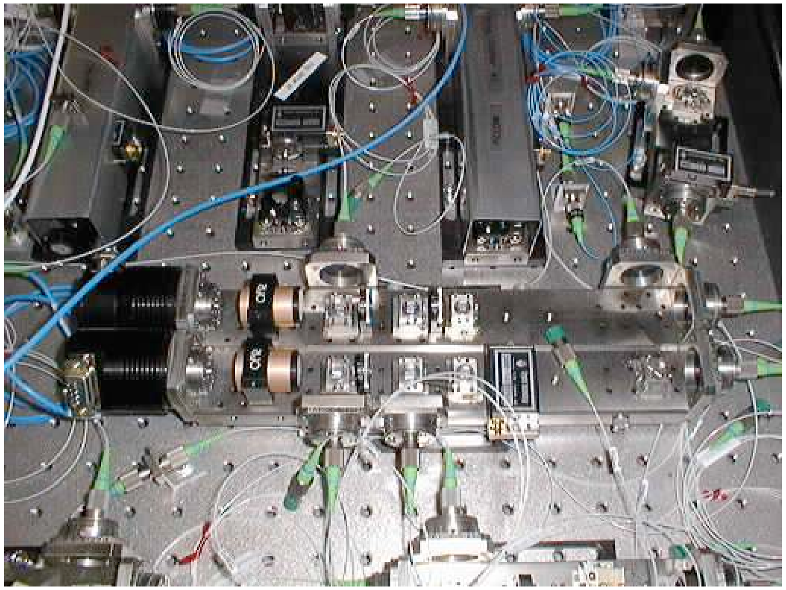

Saturation locking

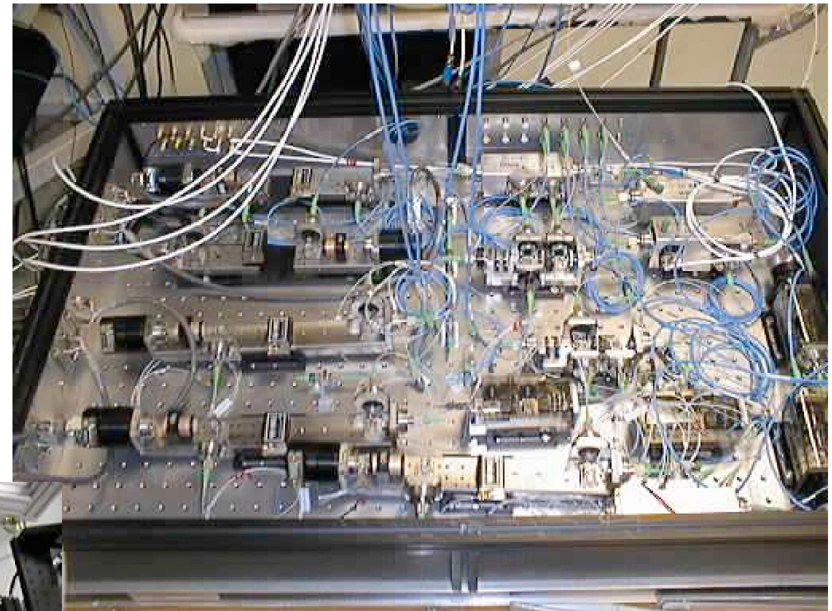

Injection locked slave laser

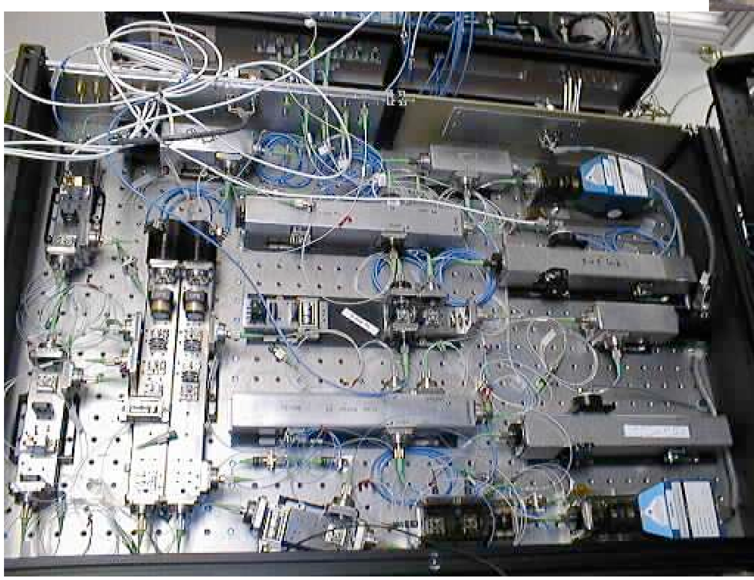

Packaged laser and optics system

1st stage system is being extensively tested while 2nd stage modules are being built.

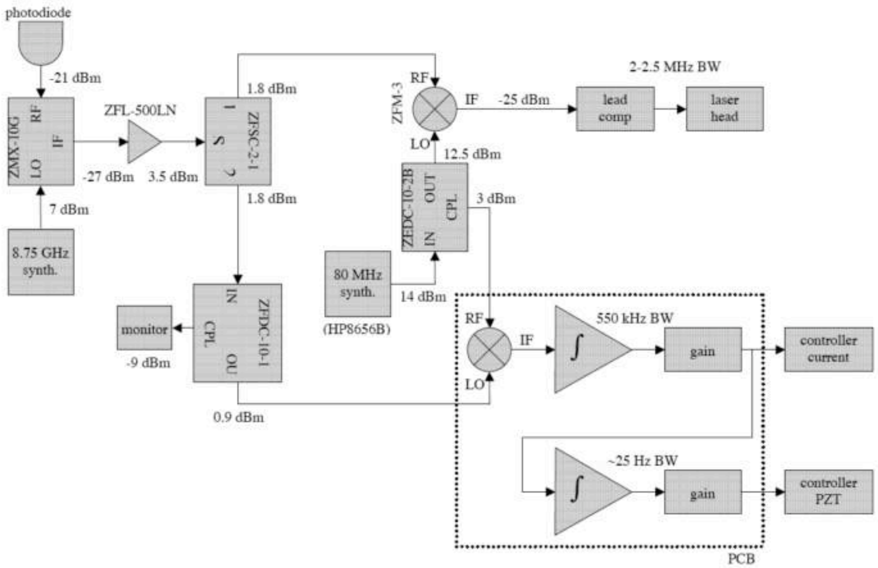
Second Stage Modules Integrated into the Optics Box

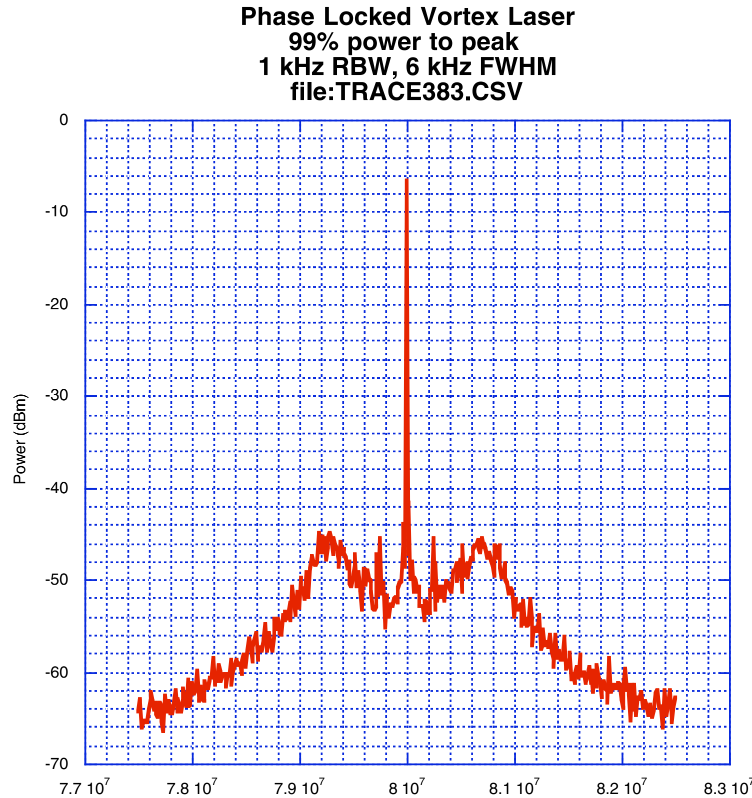






Completed and Tested Raman Phase Locking





Conclusions

- Quantum Gravity Gradiometer is a compelling technology that can significantly benefit Earth Science and solid Earth investigations
- Important progress has been made in the development of a laboratory prototype with space application in mind
- More work is underway to realize demonstration